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DESALINATION; EVAPORATION REDUCTION: ARTIFICIAL PRECIPITATION; LARGE-SCALE WEATHER AND CLIMATE MODIFICATION

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DESALINATION; EVAPORATION REDUCTION; ARTIFICIAL PRECIPITATION; LARGE-SCALE WEATHER AND CLIMATE MODIFICATION

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1. The earth's total water supply is enormous compared with the needs of mankind; only the extreme variation of its availability with time and place causes water shortages. Rain and snow falling on land areas amount to 33,000 cu.m. annually for each inhabitant of the globe. This is more than ten times the generous use of water by North Americans for all purposes, including irrigation.

2. Average figures on water supply are of little comfort to the peoples of arid lands, or to a farmer in Kansas in a year of serious drought. Rainfall averages less than 30 cm. annually (45 percent of the average for all land areas) on more than half the land surface of the earth. This is less than the average rainfall in such places as Mogadiscio, Somalia, where fresh water is in short supply.

3. Great engineering works designed to impound and distribute water, conservation measures, and multiple re-use of water can do much to offset shortages, but in many arid regions these measures will prove inadequate. Science and technology must provide ways to increase water availability.

DESALINATION

4. One obvious way to increase water availability is to recover fresh water from the enormous and widely-distributed supplies of sea water and of brackish water. Large underground stores of brackish water are located in many arid regions remote from the sea.

5. Research is being carried out in many countries for the purpose of developing practical desalination processes. Much of the work being done in the United States is coordinated and supported by the Office of Saline Water of the Department of the Interior.

6. Of the many desalination processes studied, only distillation and freezing for sea water, and electrodialysis for brackish water are now commercial[b]--commercial in the sense that they are promoted by industrial concerns. These and one other

a. Dr. Wexler had completed a revised draft of his section of this paper just before his death on August 11, 1962. His colleagues of the U.S. Weather Bureau believe that the revised draft which is reproduced here substantially expresses Dr. Wexler's intended contribution.

b. Ion exchange resins and zeolites are used to soften water, but are too expensive for the desalination of even moderately brackish water.

will be described briefly; reference 3 provides a bibliography on the subject, and references 4, 5, 6 and 7 describe recent research and development studies of a number of processes.

Multiple Distillation

7. The oldest and most used process is distillation. Total installed capacity of sea-water distillation plants is upwards of 80,000 cu.m. per day. The installations must be large and expensive if the needed energy is to be used economically.

8. Approximately 600 cal. are required to produce one gram of fresh water by simple distillation of sea water, but the great technical invention of multiple-effect distillation makes it possible to reduce this to 60 cal., or even less. Variations of the basic process include multiple-flash distillation (requiring heat transfer surface to condense vapor, but not for boiling) and vapor recompression (requiring electricity in place of heat energy). Studies indicate that for large plants it may be economical to supply the heat required by means of specially designed nuclear reactors.

Solar Distillation

9. Solar stills have received considerable study and development, as they serve to provide small quantities of water at moderate cost. Solar distillation is not a different desalination process, but a way of using solar radiation to eliminate the cost of fuel.

10. Though the energy is free, the first cost of glass-covered stills is high in relation to capacity for producing water. Current studies of inflated plastic stills may lead to less expensive designs. In the many regions of the world where the incident solar radiation averages 540 cal. per sq. cm. per day, these stills can produce 1200-1600 litres of fresh water annually from each square metre of ground area. They are being used in increasing numbers in arid regions, and have been produced commercially in Algiers and in Australia.

11. The cost of solar stills in relation to capacity is high because the solar radiation intensity is so low. To produce water at a rate equal to the withdrawal and use in North America would require single-effect stills covering an area one-quarter as large as the area of the cultivated land (4% of the total area of the U.S.).

12. It seems unlikely that solar stills can compete with large multiple-distillation units in the production of water at low cost. Solar stills can be expected, however, to find wide use in converting sea-water or inland brackish water to supply the fresh-water needs of small living groups in many arid regions of the developing countries.

Freezing Processes

13. If saline water is partially frozen and the ice crystals washed free of residual brine, the ice may be melted to produce fresh water. In one variation of the process an immiscible hydrocarbon liquid is dispersed in the saline solution; vaporization of this material provides the refrigeration to cause the water to freeze. In another process a solid hydrate is formed by contact of water and propane or other hydrate-forming substance. These solid hydrates form at temperatures greater than that at which water ice separates, and the cost of refrigeration is less.

14. Performance data on commercial desalination plants employing freezing processes are not yet available, but engineering studies suggest that freezing may be competitive with multiple-distillation for large desalination plants. One of the desalination plants to be constructed by the Office of Saline Water, U.S.D.I., will employ a freezing process. Evidently, the major process problem is the design of an efficient device to wash away residual brine from the partially-frozen mass of very fine ice or hydrate crystals.

Electrodialysis

15. This process employs membranes in the form of thin sheets of highly-hydrated organic polymers. The ion fragments of salts in solution are caused to pass through these membranes, but passage of water does not occur.

16. In contrast with distillation or freezing processes, electrodialysis consumes (electrical) energy roughly in proportion to the salt removed, rather than to the fresh water produced. For this reason, electrodialysis is more economical for the desalination of brackish than of sea water.

17. Electrodialysis is now a commercial process, and a number of plants ranging in capacity from a few hundred to 11,000 cu.m. per day have been installed in various parts of the world. Two towns in the United States employ electrodialysis of brackish water to provide municipal fresh water. Plants of this type would appear to have wide application in many arid regions where quantities of brackish water are available.

Ultrafiltration

18. This process, also known as "reverse osmosis", is not now commercial, but is the subject of considerable research in the United States. It employs thin membranes which permit the passage of water, but not of salt, when a pressure of more than about 23 atmospheres is applied (as by a piston) to sea water on one side of the membrane.

19. Too little is known about the mechanism of the membrane process to permit the selection and manufacture of useful osmotic membranes. Though promising results have been obtained, practical membranes will probably not be developed by trial and error; the basic physics of the process needs to be understood.

Desalination Costs

20. Actual data on costs of large-scale desalination operations are quite fragmentary. Sea water plants built ten or more years ago produced fresh water at costs of $0.79 - $1.27 per cu.m. Recent commercial plants report costs of $0.33-$0.53 per cu.m. These are total costs, including fixed charges, as would be calculated for an industrial enterprise. One electrodialysis plant of medium size is said to desalinate a 2200 ppm. brackish water at a total cost of $0.12 per cu.m.

21. Though the trend of costs has been downward, the curve would seem to be approaching an asymptote somewhere in the range $0.08 - $0.13 per cu.m. for the large-scale desalination of sea water with present energy costs. Though clearly a matter of opinion, it does not now appear that further engineering refinements of present commercial schemes can lead to sea water desalination costs in the range of present U.S. prices charged for irrigation water--generally less than $0.02 per cu.m. A new combination of scientific principles and technical inventions is needed, or alternatively a marked reduction in the cost of energy.

Prospects for Large Cost Reductions

22. From the foregoing, it is clear that desalination costs are now high, and that present commercial processes will find application only in rather special situations. It is of interest to speculate as to the possibilities that much less expensive processes can be developed.

23. Thermodynamics provides a basis for such a speculation. The theoretical (minimum possible) work energy required to separate one cubic metre of fresh water from sea water at 25°C., leaving a brine containing the same amount of water, is 1.09 kwh. This has a value of only about $0.01. It is worth asking why present desalination costs for sea water are 30 to 50 times this figure.

24. Part of the answer is that energy represents but a fraction of the total costs, but reduction in the energy required would lead to reduction in other costs. The actual energy is greater than the theoretical because all developed processes involve large thermodynamic losses. Reduction of these losses will reduce costs.

25. In distillation, the transport of water across the liquid-vapor interface involves little thermodynamic loss. Serious losses, however, result from the use of large temperature differences between heating steam and boiling water. Ultrafiltration, by contrast, involves large losses in the osmotic membrane; the necessary work-energy can be supplied with good efficiency by a pump. What seems to be required is a process having the high "membrane" efficiency of distillation, but with the efficient energy supply possible in ultrafiltration.

26. There is no fundamental reason why the theoretical energy should not be approached in a practical process. What is needed is basic research to provide a better understanding of the fundamental science underlying the various methods by which salt and water can be separated. This understanding will provide the basis for invention and process development.

Research Needed in Desalination

27. Desalination research and development in the United States has been devoted largely to engineering modifications and refinements of older processes. The Office of Saline Water is now embarking, however, on an expanded program of basic research.

28. A conference organized by the U. S. National Academy of Sciences was held in the summer of 1961 to consider those research areas of promise. The reports of that meeting are now available[7,8]. The conference concluded that a broader base of fundamental science is necessary in order that present processes may be improved and better ones conceived.

29. The National Academy conference strongly emphasized the need for more fundamental research on water, electrolytes, transport of both water and ions in the liquid phase, across phase boundaries, and in membrane materials. Too little is known about salt solutions. Thermodynamic properties of sea water at elevated temperatures are needed. The mechanism of scale formation and the growth of deposits on heating surfaces is not now understood. What is the effect of magnetic and electrical fields, and of sound vibrations, on transport and on scale deposition and growth? What are the barriers to transport of either water or salts across phase boundaries? A quantitative evaluation of thermodynamic losses in existing processes should focus research attention on the most important problems.

30. Basic research on nucleation and growth of crystals is needed to support

the development of new and better freezing processes, both water ice and hydrates. Large crystals are needed if they are to be easily washed free of brine--what determines their growth rates, and how can growth be effected with the least chemical potential? Hydrates which form at low pressures and at temperatures well above 0°C. have only begun to be studied.

31. Both organic and inorganic membranes need study as possible materials for the ultrafiltration process. Are hydrated ions literally filtered, or does water transport require the dissolving of water in the membrane substance? What should be the ratio of amorphous to crystalline substance in the polymeric materials? Should ion-repelling charged groups be incorporated in osmotic membranes? Though ultrafiltration is a very old idea, research on the fundamental physics of osmosis has been neglected.

32. Biology has much to offer which is relevant to desalination, and to the broad water problem. What is the structure of the natural membranes employed by plants and animals to control salt absorption? Perhaps synthetic membranes containing polypeptide chains might simulate nature and be better for osmosis. Nature employs ion pumps, which, if understood, might suggest new approaches to the manufacture of membranes for electrodialysis. Natural photosynthetic desalination organisms need study to see what lessons they offer. Can algae or sea plants be used in a cyclic-staged process, employing the properties of such substances of absorbing water preferentially?

33. This brief review suggests the nature of the needed program of basic research, as contemplated by the National Academy Conference.[8] Much money and effort have been directed, with considerable success, to the development of existing desalination processes. But the law of diminishing returns is beginning to apply, and desalination costs are too high for most water uses. The hope for inexpensive water in the future rests on the understanding of basic phenomena, which may be expected to come from a wide-ranging and imaginative program of fundamental scientific research.

EVAPORATION REDUCTION

34. Evaporation from water surfaces is a major cause of water loss. Meyers[9] estimates that the gross annual fresh-water evaporation from exposed water surfaces in the 17 U.S. western states is approximately $28.9 \cdot 10^9$ cu.m. The average annual evaporation from Lake Mead is about $0.984 \cdot 10^9$ cu.m, which is a volume greater than the storage capacity of most reservoirs in the United States. Obviously, any techniques for reducing evaporation will result in increased water supply.

35. Evaporation losses can be minimized by exposing as little water surface as possible. Therefore, if sites permit, it is advantageous to construct deep reservoirs. When several sites are available, consideration should be given to the location with the lowest rate of evaporation in making the final selection. However, the most promising method of reservoir evaporation reduction is through use of protective films. This procedure will be described in more detail later.

36. Another method of reducing water losses is the use of underground storage instead of surface reservoir storage. Some success has been achieved in the artificial recharge of ground water reservoirs and research into improved techniques is continuing. However, the extent of artificial recharge seems to be limited in some areas by the slow rate that water will percolate through the ground.

37. Evapotranspiration is not considered a loss when the moisture is being

utilized in the growth of beneficial crops and plants. However, the water used by non-beneficial plants, such as phreatophytes, should be classified as a consumptive waste. Phreatophyte eradication is one method of reducing the evapotranspiration losses, but to be effective, requires repeated and expensive treatment. Other solutions are the diversion of the water to other uses and the substitution of beneficial for non-beneficial plants. Maddock[10] stated, "It is simpler to keep water away from saltcedars [a phreatophyte] than to keep saltcedars away from the water."

38. As indicated previously, a very promising method of reducing the evaporation from lakes and reservoirs is by application of a protective film.[11] Crow and Daniel listed the characteristics of a material needed to suppress evaporation effectively without harmful effects:

"a. It must create film which has great resistance to the movement of water vapor but must not appreciably restrict the free movement of oxygen, carbon dioxide, and other gases through the water surface.

"b. It must be capable of resisting the action of wind and dust, and must be self-sealing after separation by excessive wind or boats.

"c. It must be capable of maintaining a compressed monolayer by dispensing molecules at a rate sufficient to overcome losses by wind and biological attrition.

"d. It must be nontoxic to humans, animals, and marine life."

39. Tests indicate that the most effective compounds for obtaining a film to meet these requirements are the long molecular chain alcohols, hexadecanol and octodecanol. Research on the use of hexadecanol as an evaporation suppressant was initiated by E. K. Rideal in England in 1925[12]. Research in the United States was started by Langmuir and Schaefer in 1943[13]. A comprehensive bibliography now exists on the use of monomolecular layers for reducing evaporation losses[14,15,16] but special mention should be made of the papers by Mansfield[17] and LaMer[18].

40. Hexadecanol and octodecanol are bland, almost odorless, waxy solids produced from animal, vegetable, and marine oils. They are hydrophobic-hydrophilic in character. The OH group at one end of the molecule is attracted by water and the hydrocarbon at the other end is repelled by water, causing the molecules to stand nearly vertical. Provided a sufficient supply of hexadecanol is available, the molecules will continue to be dispensed from the reserve supply until they become closely packed, forming a compressed monolayer. A monolayer is an effective barrier to water vapor only when it is compressed.

41. Laboratory tests of hexadecanol and octodecanol indicate potential reductions of evaporation of 50 percent or possibly more. However, field-scale tests in the United States using hexadecanol indicate water loss reductions of about 10 to 30 percent. Specifically, some field results were 9 percent reduction at Lake Hefner, Oklahoma[19], 14 percent at Sahuaro Lake, Arizona (1960)[20], 8 percent at Lake Cachuma, California (1961)[21], and 43 percent (1957) and 22 percent (1958) for two lakes in Central Illinois[22]. The main difficulties encountered in the field use of monomolecular layers are: (1) inefficient application of films (2) maintenance of film (3) biological effects on film. Detailed descriptions of the various techniques developed for application of the film are found in the literature.

42. A major problem during large-scale field tests is the maintenance of the protective film. At Lake Hefner, it was found to be impractical to maintain a film when wind speeds exceeded about 10 m. per sec. The wind also causes loss of film-forming material by piling it on the shore. When the shore lines had steep walls, the protective film tended to re-form. Bacteria will consume the film-forming chemicals at a rate of 0.23 to 0.34 kg per hectare per day.[23]

43. A major consideration in the application of a chemical to a reservoir is its effects on quality of water and on fish and other wildlife. The tests at Kids

Lake in Oklahoma City[24] resulted in the general conclusion "insofar as criteria of water quality, including taste, odor, color, toxicity, and other chemical qualities are concerned, nothing has been determined from this study to preclude further consideration of Lake Hefner for large-scale evaporation reduction investigations with hexadecanol." A report of subsequent tests at Lake Hafner [19], a water supply reservoir for Oklahoma City, concluded that:

"1. Public health aspects. There were no apparent toxic effects, no undesirable effects on the treatment processes of the lake water, and no interference with normal recreational uses. A large increase in bacterial content of the lake water did occur, but this was not deemed significant.

"2. Effects on wildlife. Although long term ill effects upon wildlife may be forthcoming, no acute toxicity to wildlife was observed during the investigation."

44. In summary, the application and maintenance of monomolecular films on large reservoirs present a number of problems that must be solved before the technique is economically feasible. Thus this technique for evaporation reduction cannot be expected to contribute to increased water supplies in less-developed countries in the immediate future.

45. An interesting recent development has been research to reduce transpiration from crop plants through application of fatty alcohols to soils. Roberts[25] reports that preliminary experiments in Illinois with mixtures of hexadecanol and octadecanol resulted in reduced transpiration with no apparent effect on growth of the plants. However, transpiration control is a controversial subject and some research experiments have ended with negative results. Several research studies on transpiration reduction are currently in progress.

ARTIFICIAL PRECIPITATION

46. The subject of rainmaking through the treatment of clouds with nucleating agents such as dry ice, silver iodide (ice crystal nuclei), hygroscopic particles (condensation nuclei), water sprays, and more recently, artifical electrification of clouds, has been widely investigated over the last decade and a half.[26] Experiments are continuing, and only a brief general consensus of the more carefully designed and scientifically conducted experiments completed to date will be given here, together with citations of sources of more detailed information.[27,28,29,30,31,32,33]

47. Although cloud modification and precipitation initiation had occasionally been achieved under special conditions, the claims of significant amounts of rainfall reaching the ground, prevalent in the late 1940's and early 1950's, have not been validated. There is emerging evidence, mainly from specially instrumented cloud physics aircraft, use of radar in conjunction with other experimental controls, and cloud census studies, that the microphysical events in natural clouds, which seeding techniques seek to influence, may often proceed at high efficiency for reasons which are not yet completely understood. That is, in a given cloud with rain-making potential, natural rain and snow formation is already underway by the time appreciable condensed moisture is present. Those clouds that might be susceptible to treatment are generally found to be either extremely infrequent,[34] or to contain only trivial amount of condensed moisture, when judged in terms of that required for significant quantities of rain to survive evaporation losses between the cloud base and ground. The probability of a given cloud precipitating and the amount of rainfall released appear to be dictated or at least dominated by larger scale atmospheric processes, especially the structure, vigor, duration, and extent of ascending moist air currents as they influence the lateral and vertical dimensions of cloud systems.

48. The more optimistic theoretical estimates of effects from cloud seeding are now of the order of 10 percent of the amount of increase in rainfall over that expected naturally. Similar decreases cannot be completely ruled out at this time because of both physical and statistical uncertainties. The statistical difficulties of validating such small artificial effects (small relative to the extremely large space and time variation characterizing natural rainfall) is indicated by a recent four-year series of U. S. experiments over southeastern Arizona [35] Using measured rainfall amounts from a high-density raingage network, it was estimated that well over a half century might be required to detect a 20 percent effect.

49. In summary, it appears that water supplies from the atmosphere are determined mainly by geography, by climatological factors and by the large-scale features of atmospheric circulations, and that attempts at artificial modification have not produced consistent economically significant results.

LARGE-SCALE WEATHER AND CLIMATE MODIFICATION

50. In contrast to cloud seeding, which aims at localized effects, there has been increasing speculation of late into the possibilities of large-scale (individual storms or continental, hemispheric or global scale) modification of weather and climate.

51. Large portions of entire storms, such as hurricanes, have been seeded and although interesting effects were observed on the radar screens, no conclusions could be drawn as to the effect on the intensity or movement of the storm itself.[36] Since hurricanes are prodigious producers of fresh water (Hurricane CARLA was estimated to have caused more than 40 billion metric tons of rain to fall over the Mississippi Valley in one day in September 1961--enough to have supplied the fresh water needs of the United States for more than 2 months!), it is tempting to speculate how to "tame" these storms to be benefactors rather than scourges of humanity. But much more must be learned about their origin and mechanics if Man is to probe for weak spots to exert control of one of these monstrous storms, whose energy is so tremendous that in one day, its winds could, if properly harnessed, provide the electrical energy needs of the United States for six months.

52. The present climatic regimes, including distribution of precipitation, are by-products of the large-scale circulations set into motion by unequal heating of the earth's surface by the sun--inequalities introduced by differences in latitude and the thermal contrasts between large land masses and oceans, with the rotation of the earth playing an important role. A rational explanation of the present climatic regimes, starting from basic principles and the particular land-sea configuration and other properties of our planet, has not yet been formulated.

53. One of the most interesting climatic contrasts is that existing in Africa, from the equator northward to latitude 20° where the annual rainfall decreases from 1500 mm. to practically zero. The humid southwest monsoon brings in warm, moist air south of 20° N Lat. in summer, while the hot, dry northeast trade winds cover the area to the north of this northern tropical front. T. Bergeron[37] has proposed sea water evaporation factories, powered by atomic energy, to enrich the southwest monsoon with additional humidity which would then be carried with the winds into the interior of Africa, increasing the frequency and amount of rain and at the same time moving the northern tropical front farther north because of the cooler air.[c] The economics or dynamics of this interesting suggestion were not elaborated upon but it is a good example of the sort of proposal that must await the availability of suitable mathematical models to determine its meteorological feasibility.

54. Within the past half-decade, there has been notable progress in developing mathematical models of large-scale atmospheric circulations, which, despite greatly simplified conditions, bear amazing similarities to the real atmosphere[38] [39,40]. On one of these models, basic physical parameters have been varied to observe the effect on the circulation pattern. An interesting result occurred when the poleward gradient in solar radiation was doubled: the number of planetary waves in the circumpolar westerlies thereupon decreased from 5 to 4. This would mean the elimination of an entire family of storms covering a strip of the earth's surface 8000 km. by 3000 km. Likewise, the halving of the poleward radiation gradient would mean the creation of a new storm system with its attendant precipitation pattern.

55. Despite these theoretical possibilities, no one has suggested practical means of changing the poleward gradient, which Nature does so easily as the sun changes its declination from winter to summer and back to winter. Nevertheless with more and more realistic mathematical models of the atmosphere, it may well be that vulnerable spots in the atmospheric cycle, amenable to Man's relatively puny energy and logistic resources, may reveal themselves. When this day comes two cautions must be observed: first, we must be quite sure that the models are accurate enough to predict that the desired beneficial results and not harmful unexpected changes will come about;[41] and second, that whatever is done, is done by international agreement, since such large changes in atmospheric circulations will affect many, if not all, countries of the world.

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c. Dr. Bergeron has also written a manuscript, apparently unpublished, entitled, "Possible Future Man-Made Climatic Changes", which was presented before the Department of Meteorology, Imperial College of Science and Technology, London, in early April 1961.

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